

Cherenkov radiations from Quark Plasma

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Abstract

I propose an observable to declare the formation of Quark Plasma (QP) without any doubts. It is the observation of Cherenkov photon radiations of the order of 100 MeV associated with fast light charged particles while they are penetrating hot dense mediums produced in high energy heavy ion collisions. Direct observations of Cherenkov rings associated with charged leptons decayed from Z^0 boson or Drell-Yan process which must exist earlier than the QCD medium formation and photon emissions associated with high p_t hadrons would be a definite signature of QP formation.

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Many observables have been proposed to declare the formation of Quark-Gluon Plasma (QGP) such as strong elliptic flow[1][2], jet quenching [3][4][5][6], J/ψ suppression[7, references are therein] and increase of thermal photon yields or thermal dilepton yields [8, references are therein]. However, none of above observables can make a definite statement by itself without assumptions or parameter tunings based on preferable models. One of reasons which makes it difficult to conclude is the complexity of strong interactions at the initial and final states involved in the observables. Although thermal photons, in principle, infer partially the electromagnetic interactions in the plasma, it is experimentally non trivial to measure the slight increase of the total photon yield compared to huge background from neutral pion decays[8]. In addition, it can not conclude from the experiment itself that the radiations are definitely not coming from the hadron phase after all[9]. In this letter, apart from the strong interactions, I would like to propose another observable to declare that Quark Plasma has been evidently formed by not allowing any other interpretations.

Since quarks can carry electrical charges as well as color charges, the analogy to measurements of a refractive index in a classical electromagnetic medium is worth reconsidering. Let us remind of the plasma frequency ω_p based upon classical electromagnetism (any text books can be referred, see [10] for instance):

$$\omega_p^2 = 4\pi\alpha e_q^2 \frac{N_q}{m_q} \quad (1)$$

where N_q is the number density of quarks, m_q is a mass of quark, e_q is the electrical charge in unit of electron charge and $\alpha = 1/137$. If asymptotically free quarks are assumed in an ideal gas and we focus on the aspect of electromagnetic plasma in QGP, the relation above is still valid. Suppose that genuine confinement or restoration of chiral symmetry occurs in the heavy ion collisions, the electromagnetic plasma frequency of the dense medium must become higher, because the masses of quarks are almost zero as expected from Eq.(1). Although this might be a too simplified case, it is still instructive to emphasize the direct relation between the plasma frequency and the characteristic mass of carriers in the plasma. If we assume u-quarks as dominant carriers of the plasma with its temperature $T \simeq 150 - 200$ MeV, one can estimate the number density based upon the Fermi-Dirac distribution in a relativistic ideal gas as

$$N_u = N_{\bar{u}} = \frac{g_u}{2\pi^2} \int_0^\infty \frac{p^2 dp}{1 + \exp(\sqrt{p^2 + m_q^2}/T)} \simeq 0.73 - 1.72 [fm^{-3}] \quad (2)$$

where p is the momentum, $g_u = 2 \times 9$ is the degree of freedom of u-quark and m_q is the current u-quark mass of 5 MeV. On the other hand, if we assume pions as dominant carriers of the plasma with the same temperature range, we can estimate the number density based upon the Bose-Einstein distribution in a relativistic ideal gas as

$$N_{\pi^+} = N_{\pi^-} = \frac{g_\pi}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp(\sqrt{p^2 + m_\pi^2}/T) - 1} \simeq 0.04 - 0.11 [fm^{-3}] \quad (3)$$

where g_π is 1 and m_π is the mass of charged pion. With Eq.(1), (2) and (3) we can estimate the electromagnetic plasma frequency $\omega_p(u\bar{u})$ and $\omega_p(\pi^\pm)$ in the $u\bar{u}$ and $\pi^+\pi^-$ plasma as;

$$\omega_p(u\bar{u}) = \sqrt{4\pi\alpha(e_u^2 + e_{\bar{u}}^2)\frac{N_u}{m_u}} \simeq 238 - 366[MeV] \quad (4)$$

and

$$\omega_p(\pi^\pm) = \sqrt{4\pi\alpha(e_{\pi^+}^2 + e_{\pi^-}^2)\frac{N_\pi}{m_\pi}} \simeq 20 - 33[MeV]. \quad (5)$$

What should be stressed here is that there is a clear distinction between Eq.(4) and (5) due to $m^{-1/2}$ dependence. This is an essentially important fact for the following discussions.

In order for Cherenkov radiation to be observed, following necessary conditions must be satisfied;

$$\delta n(\omega) = n(\omega) - 1 > 0 \quad (6)$$

$$\cos\theta = 1/\beta n(\omega) \quad (7)$$

where ω is a frequency to discuss the dispersion property, $n(\omega)$ is a refractive index of a dense medium, $\delta n(\omega)$ is the deviation of it from bear vacuum, and θ is the emission angle from the direction of a fast charged particle. In order to discuss frequencies of emitted Cherenkov photons, let us remind that a dielectric constant $\epsilon(\omega)$ of an electromagnetic medium has a simple form:

$$n(\omega)^2 = \epsilon(\omega) = 1 + \frac{\omega_p^2}{\omega_R^2 - \omega^2} \quad (8)$$

where ω_R is a resonant frequency. It is natural to expect that some resonances appear in loosely bound quarks or hadrons during the phase transition from a deconfined to confined state. Here the dumping term in the more general form was omitted for the simplicity, by which the intention of this letter is not altered. In a high frequency limit $\omega \gg \omega_R$, the relation becomes

$$n(\omega)^2 = \epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \quad (9)$$

where Cherenkov emissions can not be expected due to $\delta n(\omega) < 0$. As the frequency approaches $\omega \simeq \omega_R$, the anomalous dispersion appears and $\epsilon(\omega)$ steeply fluctuates around unity. Below the resonant frequency $\omega < \omega_R$, $\delta n(\omega) > 0$ is satisfied and Cherenkov radiations may occur. It is a well-know fact that the frequencies of emitted Cherenkov photons ω_C are limited in a frequency band $\omega_0 \leq \omega_C < \omega_R$, where ω_0 must satisfy $n(\omega_0) > 1/\beta$ [10]. Since the plasma frequency is higher than the resonance frequency, if some of observed Cherenkov photons satisfy the following relation

$$\omega_p(\pi^+\pi^-) \ll \omega_c < \omega_R < \omega_p(u\bar{u}), \quad (10)$$

it directly indicates that the dominant carriers of the plasma are quarks, because the hadronic matter can not emit Cherenkov photons exceeding $\omega_p(\pi^\pm)$. This is a definite

signature to declare the formation of Quark Plasma as well as the restoration of the chiral symmetry. In other words, this measurement provides us a direct way to measure the bare quark mass near the phase transition. In addition, if we could measure the emission angles with respect to fast light charged particles as well as those energies, we can directly measure the refractive index by experiments and eventually investigate the dispersion property of the hot dense medium. With $\beta = \sqrt{1 - (\frac{m_{ch}}{E_{ch}})^2}$ where m_{ch} and E_{ch} are mass and total energy of a fast charged particle, the sensitivity to δn can be discussed by the relation

$$\delta n > 1/\beta - 1. \quad (11)$$

As the penetrating light charged particles, if we take electrons from $Z^0 \rightarrow e^+e^-$ which must exist much earlier than the QCD medium formation, it is sensitive to $\delta n > 6.0 \times 10^{-11}$ in a produced medium. If we take hard struck u-quarks of 10 GeV/c and $m_q = 5\text{MeV}$ as sources of high p_t hadrons, it is sensitive to $\delta n > 1.3 \times 10^{-7}$, though in this case β must be modified due to strong interactions between the leading quark and the medium, which would distort the relation in Eq.(7). The most important but least known factor is whether the medium with $\delta n > 0$ could emerge or not during the phase transition. However, whatever the mechanism is, as long as the Cherenkov rings above ~ 100 MeV associated with preexisted charged leptons were observed, one would be able to clearly state the dominant carriers of the medium are not pions but light quarks apart from the complexity of the gluonic matter, since charged leptons see only electromagnetic aspect of the QGP.

The estimated photon energy between Eq.(4) and (5) is experimentally measurable even in the present detector design such as PHENIX detector at RHIC [11][12] and ALICE detector at LHC[13], both of which are capable of measuring photons as well as charged leptons and hadrons. Even with huge photon background conditions, it would be feasible to reconstruct Cherenkov rings if we utilize special tools such as wavelet analysis[14], as long as the emission angle is reasonably large enough compared to the granularity of photon detector segments. If high p_t light quarks are regarded as leading particles in a medium, the Cherenkov rings can not be easily reconstructed. In this case one may seek the unexpected fluctuations between high p_t hadrons and photons well beyond the fluctuations expected from jet fragmentation. Unfortunately, in the case where δn is quite small, the photons are collinearly emitted with the penetrating charged particles, then it would be difficult to show the existence of rings. However, even in such a case, E/p , the fraction of measured energy E in electromagnetic calorimeters to measured momentum p in tracking devices for each high p_t charged particle could be a good observable. If E/p values of high p_t charged particles are increased due to collinearly emitted photon energy compared to fluctuations of expected E/p from accidentally associated photon energies in the high multiplicity environment of heavy ion collisions, it would be a hint of the existence of Cherenkov radiations.

In summary, the observation of Cherenkov photon radiation of the order of 100 MeV associated with fast charged leptons from the hot dense medium is a definite signature of Quark Plasma formation. Although the observable focuses on only the electrical charge

aspect, it evidently indicates the lightness of carriers in the plasma. It also opens a way to investigate the dispersion property of a formed hot dense medium by measuring emission angles and the wavelengths of Cherenkov photons. The cut-off or upper limit on the energy of the emitted Cherenkov photon is within the measurable energy range covered by the existing detector designs. Although the observation of Cherenkov rings is the clearest signature, photon and high p_t hadron correlations or the large fraction of measured energy to measured momentum of charged particles indirectly indicates the existence of Cherenkov radiations. I hope that more quantitative discussion on δn including the color charge aspect of the plasma would follow this letter in connection with this observable.

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References

- [1] STAR, K.H. Ackermann et al., Phys. Rev. Lett. 86 (2001) 402, nucl-ex/0009011.
- [2] PHENIX, S.S. Adler et al., (2003), nucl-ex/0305013.
- [3] PHENIX, K. Adcox et al., Phys. Lett. B561 (2003) 82, nucl-ex/0207009.
- [4] STAR, C. Adler et al., Phys. Rev. Lett. 89 (2002) 202301, nucl-ex/0206011.
- [5] PHENIX, S.S. Adler et al., Phys. Rev. Lett. 91 (2003) 072301, nucl-ex/0304022.
- [6] PHENIX, S.S. Adler, (2003), nucl-ex/0308006.
- [7] NA50, H. Santos et al., (2003), hep-ex/0306004.
- [8] WA98, T. Peitzmann, (2000), nucl-ex/0009014.
- [9] D.K. Srivastava, Eur. Phys. J. C10 (1999) 487.
- [10] J.D. Jackson, Classical Electrodynamics (JOHN WILEY & SONS, Inc., 1974).
- [11] PHENIX, D.P. Morrison et al., Nucl. Phys. A638 (1998) 565, hep-ex/9804004.
- [12] PHENIX, N. Saito et al., Nucl. Phys. A638 (1998) 575, hep-ex/9805003.
- [13] J. Schukraft, Pramana 57 (2001) 345.
- [14] I.M. Dremin, (2000), hep-ph/0011110.